Development of the Crosstrack Infrared Sounder (CrIS) Sensor Design

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ABSTRACT

The Crosstrack Infrared Sounder (CrIS) is one of the key sensors now under development for the National Polar-orbiting Operational Environmental Satellite System (NPOESS) program, which is the follow-on to the current DMSP and POES meteorological satellite systems. CrIS is a interferometric sounding sensor which accurately measures upwelling earth radiances at very high spectral resolution, and uses this data to construct vertical profiles of atmospheric temperature, moisture and pressure. These profiles are also called Environmental Data Records, or EDRs. The purpose of this paper is to describe the top level trade studies that led to the selection of the overall CrIS sensor design. Most of these trade studies involved a tradeoff between system performance (EDR performance) and relative system cost. This paper discusses how EDR performance was determined for different trade study options, and reviews the key design and cost tradeoffs that led to the selection of the CrIS design.

Keywords: interferometer, fourier transform spectrometer, sounder, remote sensing

1. BACKGROUND

Since the 1970s, the United States has relied on two separate low-earth-orbiting (LEO) meteorological satellite systems (POES for civilian users and DMSP for military users) to provide remote sensing data that is used for weather forecasting and other critical applications. Because these two systems have sensors that share many similar characteristics, a decision was made in the early 1990s to "converge" these two meteorological systems into a single system for the next century. This system, known as NPOESS (National Polar-orbiting Operational Environmental Satellite System), is to provide a single low-earth orbiting satellite system that can fulfill the missions of both the civilian and military users.

The Crosstrack Infrared Sounder (CrIS) is one of the primary sensors within the NPOESS system. Its mission is to collect upwelling infrared spectra at very high spectral resolution, and with excellent radiometric precision. This data is then merged with microwave data from other sensors on the NPOESS platform to construct highly accurate temperature, moisture, and pressure profiles of the earth's atmosphere. Collectively, the CrIS and microwave sensors are referred to as the CrIMSS (Crosstrack Infrared and Microwave Sounding Suite). The profiles produced by this suite are a primary input to numerical weather forecast models, and their improved accuracy offer enhanced forecast accuracy on a global basis.

In 1997, ITT Industries (ITTI) began work on a Phase 1 study program sponsored by the NPOESS Integrated Program Office (IPO). The objective of this study program was to examine numerous sensor configurations to arrive at a "best value" approach, and develop a complete design for the CrIS sensor and algorithms. The study culminated in a Preliminary Design Review in April 1999. The Phase 2 program is now working towards completion of a Critical Design Review in 2002, by which time a flight-like prototype of the CrIS sensor will be built and fully tested. The first delivery of a flight sensor will occur in 2004 to support a first flight on the NPOESS Preparatory Program demonstration satellite in the 2006 timeframe.

The purpose of this paper is to discuss the key cost-versus-performance trade studies that led to the selection of the CrIS sensor design. In addition, we summarize the top-level performance parameters of the selected CrIS system.

2. CrIS SYSTEM OVERVIEW

As illustrated in Figure 1, CrIS is part of the overall cross-track scanning CrIMMS suite (Cross-track Infrared and Microwave Sounding Suite), which is one of the sensor suites onboard the NPOESS satellite. CrIMMS will be composed of CrIS plus the Advanced Technology Microwave Sounder (ATMS). The NPOESS satellites operate in a polar orbit at a nominal altitude of 833 km. During typical operations, CrIS will collect radiance data over an extended period of time (typically 1.25 orbit), then downlink this data to ground stations for processing.

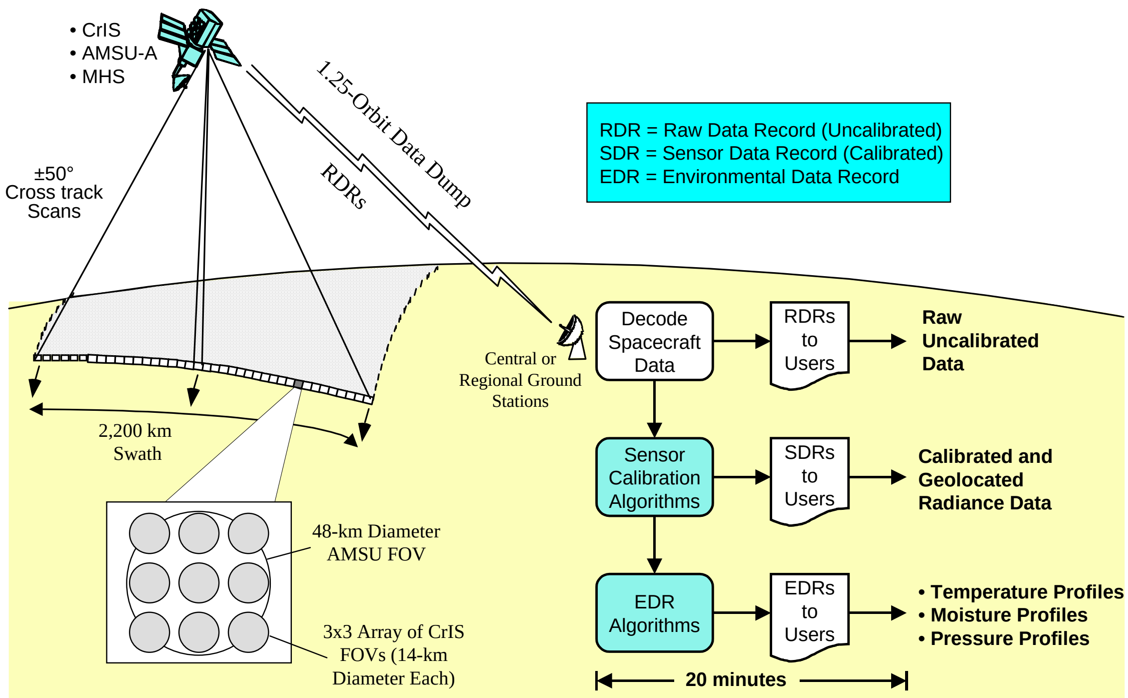


Figure 1. Overall Architecture of the CrIS System (need ATMS version)

The types of data output by the CrIS system come in different forms depending on the users' particular needs. To support these needs, three types of CrIS data products are provided. Raw Data Records (RDRs) are uncalibrated raw data records (also commonly referred to as Level 3 data products) in interferogram format. Sensor Data Records (SDRs) are data records that have been converted to spectra, have had spectral and radiometric corrections applied, and which have been geolocated (comparable to Level 2 data products). Environmental Data Records (EDRs) are the resultant profiles of temperature, moisture, and pressure, and are produced by passing the CrIS SDRs and microwave SDRs through EDR algorithms to generate the atmospheric profiles (to produce Level 1 data products). CrIS raw data that is collected during one or more orbits is downlinked to central to regional terminals, where the data is converted to SDRs and ultimately to EDRs.

3. SELECTION OF THE "BEST VALUE" CRIS SENSOR DESIGN

The CrIS program has been a pioneer in applying the concept of cost effectiveness to an operational satellite program. Since its inception, the primary objective of the CrIS program has been to deliver the highest-quality data products possible, and the smallest and lightest sensor possible, while meeting aggressive cost constraints. The goal was to develop a "Best Value" CrIS system design; that is, a system that provides the best combination of performance and cost. In this context, "performance" is defined to be EDR-level performance for each of the CrIS EDRs (temperature, moisture, and pressure). Early in the program, the NPOESS IPO established minimum "threshold" EDR performance requirements for CrIS, as well as ambitious EDR "objectives". The IPO's goal was to achieve better-than-threshold EDR performance, but consistent with the CrIS funding profile and with spacecraft accommodation parameters such as weight, volume, power, and data rate.

The first step in realizing the goal of a "best value" CrIS system was the development of an accurate System Performance Simulation (SPS) that could be used to evaluate the performance of different sensor and algorithm approaches, and an accurate cost model that could be used to assess the relative life-cycle costs of the various options.

The SPS evolved from elements of simulations that were developed by ITT Industries (ITTI) as parts of prior programs such as GHIS[1] (GOES High-Resolution Interferometric Sounder) and other IR&D simulation development programs. At the heart of the SPS is a detailed sensor simulation, that allows top-level sensor performance parameters (such as NEdN and radiometric uncertainty) to be determined based on parametric inputs for a number of different detailed sensor design parameters (such as aperture, detector type, detector temperature, or signal processing approach). This sensor model was tied to a set of EDR retrieval algorithms developed by Atmospheric Environmental Research (AER), one of ITTI's teammates on CrIS[2,3]. The EDR algorithms are able to determine the accuracy of the retrieved EDR profiles for different sets of sensor performance characteristics. The combined SPS is able to accurately determine how different sensor design options impact overall EDR mission performance.

The SPS provided the "performance" axis of the cost-versus-performance trade space, but another model was needed to accurately determine the costs of different sensor and algorithm approaches. ITTI used the SEER cost model for this purpose. SEER is a parametric industry-standard cost modeling program that ITTI has adapted to its space hardware programs. SEER has been compared to prior ITTI space hardware programs, and calibrated to accurately reflect the costs of new programs. SEER has the advantage that it can model costs to a very fine level of detail, using an in-depth set of input sensor parameters.

The combination of the SPS and SEER made it possible to accurately construct a cost-versus-performance trade space for CrIS, and then use this information to select a "best value" CrIS system design. These types of trade studies were then conducted for a number of different sensor and algorithm parameters. In all, over twenty different cost-versus-performance relationships were established, and trade studies were conducted to select the best combination of values for the CrIS system.

A number of different sensor-level parameters can influence the overall EDR performance of the system. Figure 2 illustrates these relationships in the form of an allocation tree. To complicate the problem further, many of the sensor parameters are interrelated. For example, decreasing the size of the FOV tends to improve EDR performance because there is an increased probability of a cloud-free sounding; at the same time, the smaller FOV has a larger NEdN, which degrades the EDR performance. For all of these parameters, interdependencies must be taken into account in order to arrive at a truly optimal design solution. In addition, care was taken not to violate any of the key physical requirements imposed by the IPO, such as mass, power, or total volume.

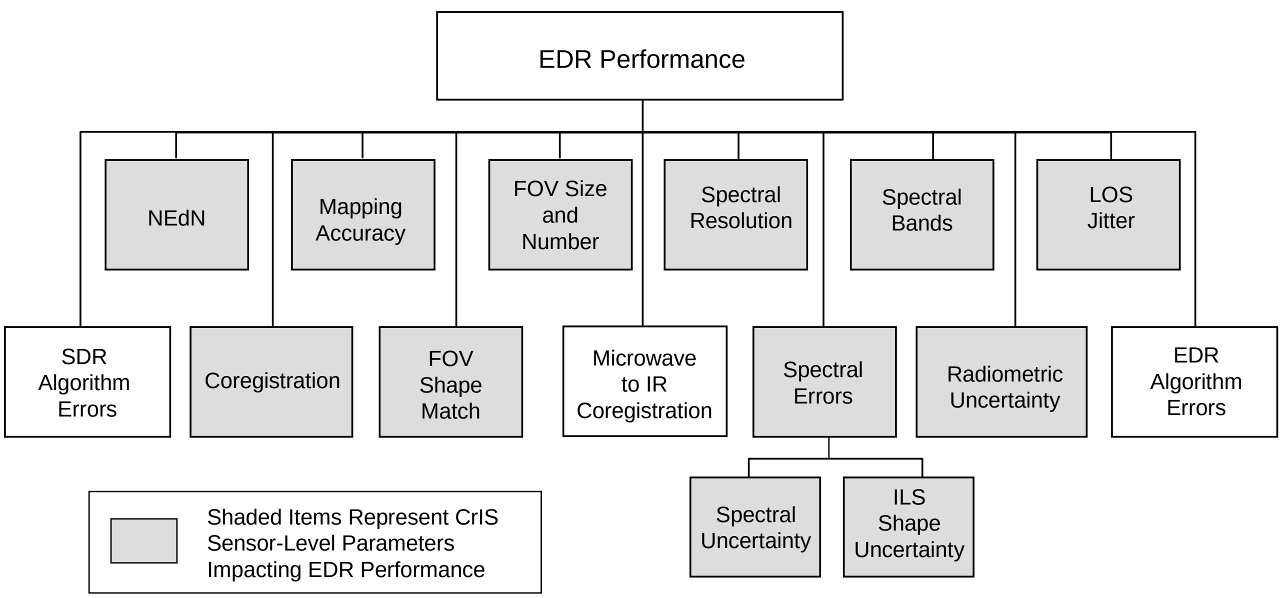


Figure 2. Sensor and Algorithm Parameters That Influence Overall EDR Performance

4. KEY CrIS TRADE STUDIES

Four key trade studies tended to drive the overall architecture of the CrIS sensor. These trades involved sensor parameters that determined the major characteristics of the sensor design. These four trade studies were:

1) Aperture Size
2) Number of Spectral Bands
3) Detector Type / Detector Cooler Type
4) FOV Size / Number of FOVs

As noted earlier, two of these trade studies were not simple single-dimensional trades, but involved complex interactions between multiple sensor subsystems. These four trade studies are discussed in more detail below.

Aperture Size: The selection of the CrIS aperture size was a fundamental decision that impacted almost all other aspects of the design. A large apertures tends to improve EDR performance by increasing the sensitivity of the sensor (or improving its signal to noise ratio). However, larger apertures also tend to be more expensive and take up more volume and mass, due to the larger size of optical elements and support structure. The objective of this trade study was to examine the cost and performance of different sensor aperture sizes, and select an optimum value for CrIS. The results of this trade study are illustrated in Figure 3.

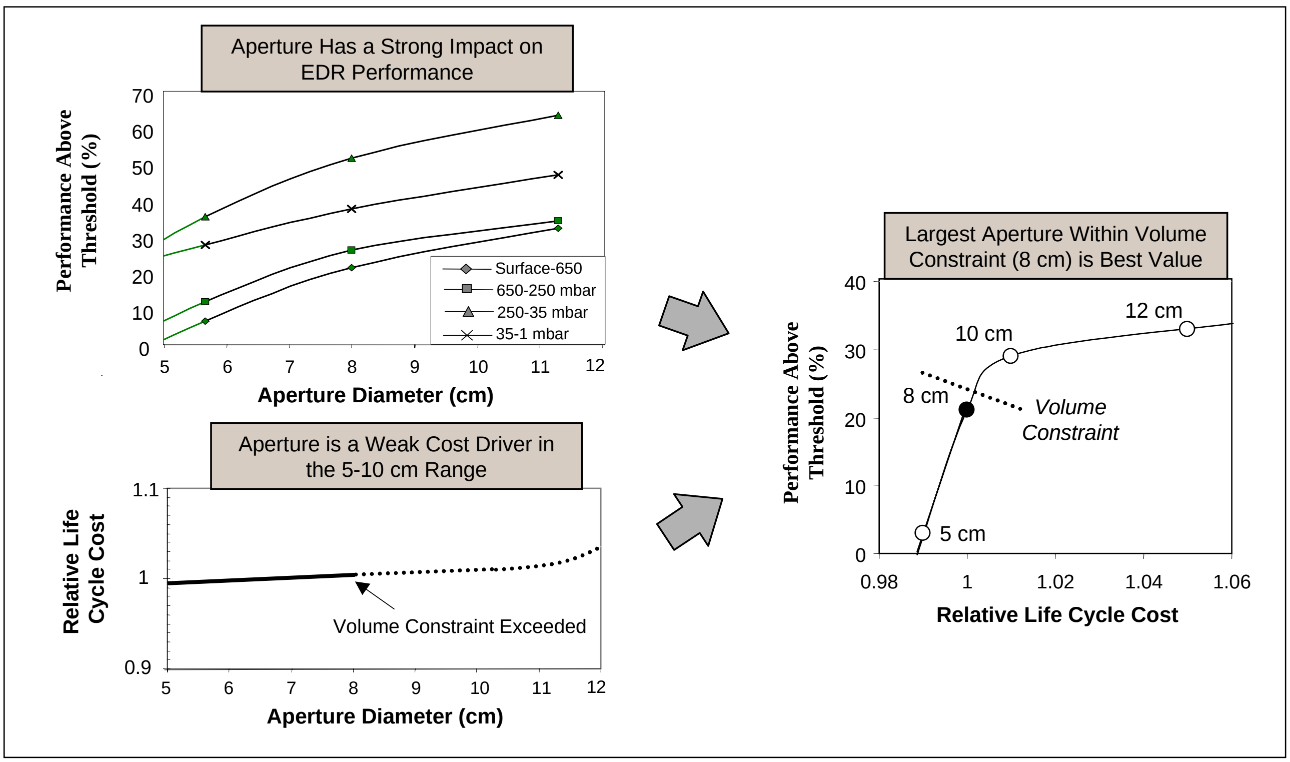


Figure 3. Aperture Trade Study Identified 8.0 cm as Optimum for CrIS

Figure 3 shows that EDR performance is a relatively strong function of aperture size; that is, even relatively small increases in aperture produce noticeable improvements in EDR performance due to the improved radiometric sensitivity offered by larger apertures. This is illustrated in the upper left panel of Figure 3, which is an output of the CrIS SPS. The four curves indicate performance at different altitudes in the atmosphere, and the vertical axis is Temperature EDR performance margin above threshold (i.e., a positive value indicates that EDR performance is better than the IPO-defined minimum requirements). The results clearly favor maximizing the CrIS aperture size. To establish the cost axis of the cost-versus-aperture graph in the lower left panel of Figure 3, we used the SEER model, in conjunction with cost estimates from team members. We found that, over the range of apertures considered here, the cost relationship is relatively weak. That is, the size and cost of the optics and structure of CrIS are not dominating the cost of the sensor, until the aperture exceeds about 10 cm in diameter. At that point, aperture size begins to become a cost driver.

When we combine these two graphs in the right half of Figure 3, we see that a meaningful cost-versus-performance relationship can be constructed. A clear "knee in the curve" becomes apparent at an aperture size of about 10 cm, and given no other constraints, this would have been our chosen aperture for CrIS. However, there is also a volume constraint imposed by spacecraft packaging considerations, and CrIS layout studies found that this volume constraint limits the available aperture to approximately 8 cm. Thus, the trade study determined that an 8 cm aperture was optimum for CrIS.

Number of Spectral Bands. Another fundamental design decision involves the selection of the spectral coverage of the CrIS sensor, and the number of spectral bands into which this coverage is subdivided. Atmospheric retrieval physics tends to place clear requirements on the spectral regions of interest for CrIS. Of primary importance are the 667-800 cm^{-1} region (which is critical for Temperature EDR retrievals), the 1210-1700 cm^{-1} region (critical for Moisture EDR retrievals), and the 2150-2380 cm^{-1} region (important to support Temperature EDR retrievals). In addition, the region near 1000 cm^{-1} was considered to be of interest because it provides information useful for ozone profiling (this is not a specific CrIS mission, but the data in this spectral range is potentially useful to other sensors on NPOESS).

Because the overall CrIS spectral range is so broad, trade studies conducted early in the program quickly identified the advantages of splitting the CrIS spectral range into three discrete spectral bands: LWIR (nominally 650-1095 cm^{-1}), MWIR (1210-1750 cm^{-1}), and SWIR (2155-2550 cm^{-1}). This splitting allows the detectors and optical coatings to be optimized for a smaller spectral range, providing improved overall performance in each of the three bands. However, more spectral bands increases cost due to the larger number of optical components, more detectors, and increased testing. For this reason, a trade study was conducted to determine if the number of bands could be reduced.

The trade study compared the baseline 3-band system to a 2-band system which combined the MWIR and SWIR bands into a single large spectral band. The disadvantage of this approach is that the SWIR NEdN performance is degraded due to the roll-off in detector and optical coating performance at the shorter wavelengths. This can lead to a degradation in Temperature EDR performance under some conditions. But the advantage is that cost is reduced due to the elimination of some optics, one set of detectors, some signal processing electronics, and some testing costs. Figure 4 summarizes the results of the trade study.

The upper graph in Figure 4 illustrates that the Temperature EDR performance of the 2-band system at very low altitudes is inferior to the 3-band system. In addition, the three-band system is somewhat more robust, in that it can improve the accuracy of the surface emissivity retrieval, and can under some conditions make use of the SWIR band to better identify the presence of clouds. The cost comparison shown at the lower left of Figure 4 illustrates that some cost savings would be realized by going to a 2-band system (about 9% total life cycle cost). However, the conclusion of this trade study was that the small reduction in cost was not sufficient to offset the reduction in EDR performance. Therefore, the 3-band system was retained as the CrIS baseline. It should be noted, however, that on a global average basis, the reduction in EDR performance is lessened (i.e., it is only over a limited range of conditions that the SWIR band is of added utility).

Additional spectral band trade studies also examined the impacts of different spectral widths in the LWIR and MWIR bands. These trade studies tended to find limited benefits from reducing the spectral range (usually in terms of reduced photon flux levels entering the passive cooler), but these benefits were not sufficient to justify the loss in overall system performance.

Detector Type / Detector Cooler Type. Once the spectral bands had been selected, it was necessary to select the optimum type of detector to use in each band. Numerous types of detectors have been used in previous sounding sensors (e.g., InSb, HgCdTe), but HgCdTe detectors tend to have a number of advantages, including excellent sensitivity and good producibility. As a result, these were baselined for use on CrIS. However, it was also necessary to select between photo-conductive (PC) and photo-voltaic (PV) HgCdTe detectors. PV detectors have the critical advantages of much better linearity and improved

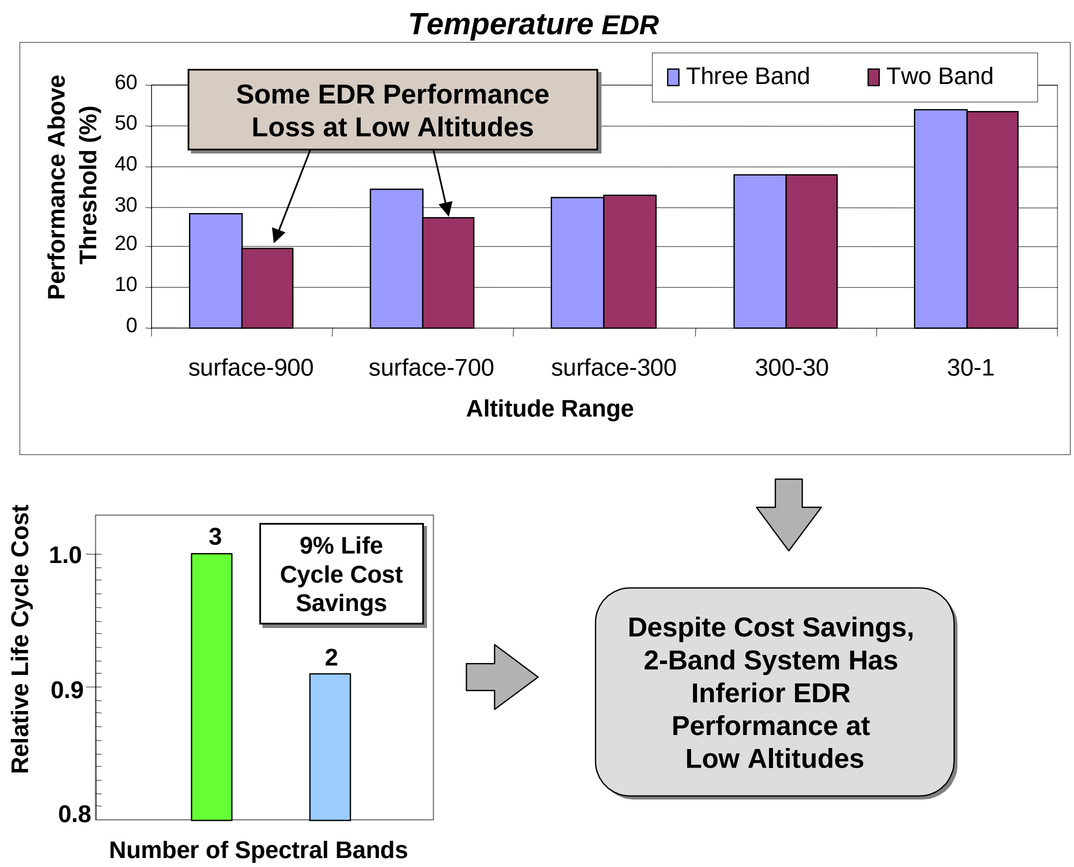


Figure 4. Number of Spectral Bands Trade Study Findings

sensitivity; thus, PV detectors are the preferred choice for CrIS. Unfortunately, the state of the art of PV HgCdTe at the time of the start of the CrIS contract was inadequate to allow their use in the CrIS LWIR band. PV detectors had already been adequately demonstrated in the SWIR and MWIR bands, but not LWIR, especially at the relatively large detectors sizes (1000 um) needed for CrIS (due to its pupil-imaging optical design). During the CrIS Phase 1 program, cooperative IR&D efforts between ITT and Boeing successfully demonstrated that PV HgCdTe technology was feasible at CrIS LWIR wavelengths[4], but only if the detector temperature could be kept below about 85K. Above this temperature, the PV detectors experienced a large increase in noise levels.

This finding caused the LWIR detector trade study to be expanded to include the type of cooler to use for CrIS (i.e., an active cooler versus a passive radiant cooler). Typical passive radiant coolers have difficulty achieving temperatures below 85K, using the radiator area available for the IPO-specified CrIS envelope. As a result, the trade study examined three types of coolers: 1) a typical 3-stage passive cooler, 2) an advanced 4-stage passive cooler, and 3) a mini-pulse tube active cooler. The 4-stage passive cooler used an innovative feature in which the LWIR detectors are mounted on the coldest 4th stage of the cooler, while the MWIR and SWIR detectors (which do not have to be as cold) are mounted on the 3rd stage. Placing only the LWIR detectors on the 4th stage minimizes the heat load on the 4th stage, and allows it to reach colder temperatures. For the CrIS geometry, this type of cooler is able to achieve temperatures of about 81K at the 4th stage, and about 98K at the third stage. In contrast, the standard 3-stage passive cooler is limited to temperatures of about 90K (for all 3 bands), making the use of PV detectors in the LWIR band impractical. The mini-pulse tube cooler examined for CrIS is capable of even colder temperatures (about 65K for all three bands), but has the disadvantages of increased power, increased complexity, and higher cost.

The first step in evaluating this combined Detector Type / Cooler Type trade study was to assess the relative performance of the three cooler options. The upper left panel of Figure 5 illustrates the Temperature EDR performance of the three systems (i.e., a 3-stage passive cooler with PC LWIR detectors, and 4-stage passive cooler with PV LWIR detectors, and an active cooler with PV LWIR detectors).

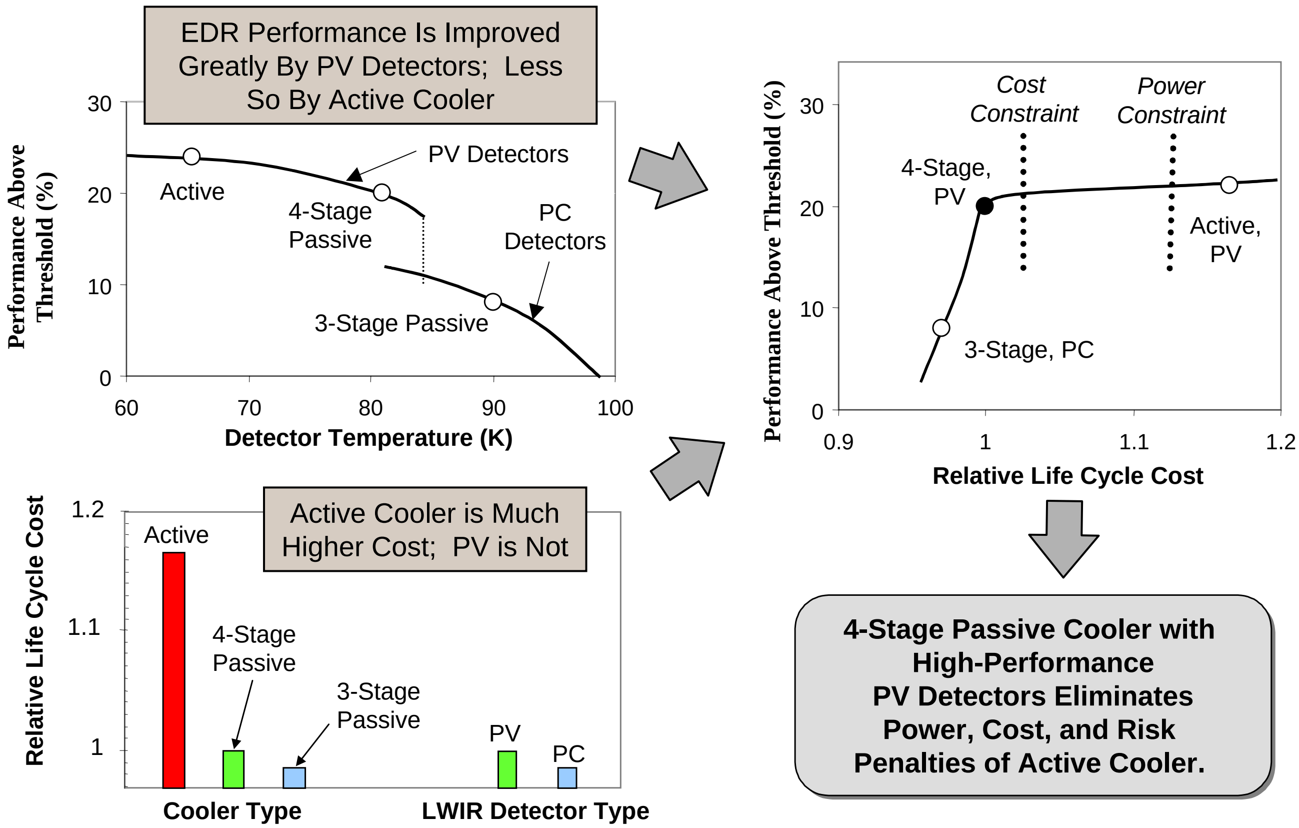


Figure 5. Detector Type / Cooler Type Trade Study Results

It is immediately evident from this figure that PV LWIR detectors offer substantial EDR performance gains. This is due to two factors. First, the intrinsically better sensitivity of PV detectors (compared to PC) results in improved CrIS NEdN performance in the LWIR band, which is critical for EDR performance. Second, the improved linearity of PV detectors reduces the radiometric uncertainty of the CrIS sensor, which is also an important EDR performance driver.

It is interesting to note that the incremental EDR performance improvement produced by the active cooler (relative to the 4-stage passive cooler) is relatively small. This is because once detector temperatures drop below about 70K, detector noise is no longer the limiting factor in LWIR NEdN performance (i.e., the system becomes background limited). As a result, the LWIR NEdN performance of the actively cooled system is not much better than the 4-stage passive cooler.

The next step in the trade study was to compare the relative costs of the three systems, shown in the lower left panel of Figure 5. Only small cost differences were found between the PV and PC detectors, and between the two types of passive coolers. However, the added cost of the active cooler is significant.

When the cost and EDR performance data are combined (upper right panel of Figure 5) it is obvious that the 4-stage passive cooler with PV detectors is the optimum cost-versus-performance choice for CrIS. In addition, it was found that the active cooler option violated both the IPO-imposed cost and power constraints for CrIS, and would be a severe packaging challenge for the tight CrIS volume. All of these factors led to the selection of the 4-stage passive cooler with PV detectors as the CrIS baseline.

FOV Size and Number. A final critical CrIS trade study involved the selection of the size and number of CrIS FOVs. In order for CrIS to meet its spatial coverage requirements, it must utilize a field of regard (FOR) that is roughly 3.3-degrees square (which also roughly matches that of the microwave sensors with which CrIS operates). Within this field of regard are the individual CrIS fields of the view (FOVs); the FOV is the spot on the ground viewed by each individual detector. The IPO-imposed requirement of a maximum FOV size of 15 km meant that at a minimum, the CrIS FOR must contain at least 9 FOVs, arranged in a 3x3 array. However, it was not clear if such a 3x3 configuration was optimum for CrIS, or if the use of larger than 3x3 arrays might be beneficial in terms of CrIS EDR performance.

To address this question, three other design concepts were evaluated: a 4x4 set of FOVs using 10 km diameter FOVs, a 5x5 set of FOVs using 8 km FOVs, and a 6x6 set of FOVs using 6 km FOVs. As the number of detectors is increased, the heat load on the cooler increases. As a result, it was found that it was not practical to use a 6x6 array of PV LWIR detectors while still using a 4-stage passive cooler; thus, this option also uses an active cooler.

The advantage of the smaller, more numerous FOVs is that the probability of a cloud-free sounding increases (i.e., it is more likely that one of the FOVs will view a “hole” in the clouds). Since cloud-free soundings produce more accurate EDRs, this is an advantage. However, smaller FOVs also have intrinsically worse NEdNs (due to the reduction in etendue), which tends to degrade the EDR performance. Thus there are two offsetting effects at work.

The best way to evaluate this trade study was to simulate the performance of each of these candidate systems against a realistic earth scene containing representative cloud patterns. The process used is illustrated in Figure 6. An extended cloudy scene (taken from the Kiev scene of the GCI Toolkit) was used as the input condition. Next, the various FOV formats (i.e,. 3x3, 4x4, etc.) were overlayed on this scene, cloud fractions in each FOV were evaluated, and simulated retrievals were

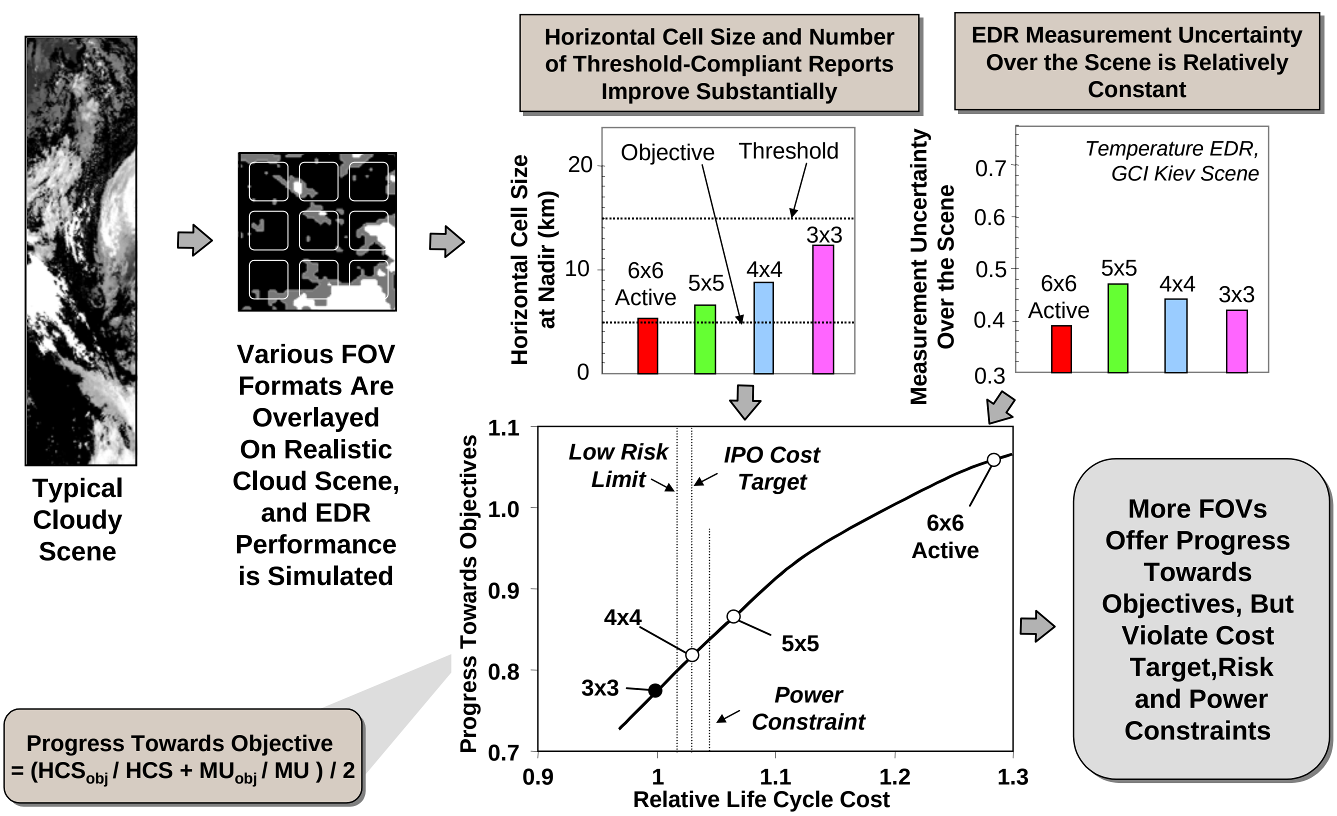


Figure 6. FOV Size and Number Trade Study Results

performed. Overall performance was evaluated by determining the Temperature EDR performance averaged over all of the CrIS FORs. The results are shown in the upper right panel of Figure 6, which shows that the EDR measurement uncertainty averaged across the full scene does not change much as a function of the array size. It appears that the improved probability of cloud-free soundings is very nearly cancelled out by the higher NEdN per measurement.

However, another important advantage of the larger arrays is that the increased number of FOVs tends to increase the number of EDR reports that are potentially useful to meteorological users. This is reflected in another IPO-defined EDR performance parameter – the Horizontal Cell Size (HCS). The IPO established an ambitious EDR Objective of 2 km for the CrIS HCS. To take this into account, we established a figure of merit for this trade study that combined both the EDR Measurement Uncertainty and the EDR HCS. Called "Progress Towards Objectives", this figure of merit is plotted in the lower panel of Figure 6. It indicates that larger arrays tend to have better performance against the figure of merit. However, the larger arrays are also seen to quickly violate a number of other IPO-imposed constraints, such as cost and power. In addition, it was found that array sizes beyond 3x3 tend to introduce some additional technical risk into the design. Since another IPO objective was to limit higher-risk technologies used in CrIS, this was also a factor in the evaluation.

The overall conclusion of this trade study is that it appears that larger arrays are of interest for CrIS, and do have some performance advantages. However, given the existing CrIS constraints, the best-value baseline design for CrIS appears to be a 3x3 array. The final design approach selected for CrIS was to use a 3x3 array as a baseline, but to include design features in the CrIS sensor design that make it relatively straightforward to increase the array size to 4x4 or 5x5 if the user community desires this upgrade in the future.

5. OTHER CRIS TRADE STUDIES

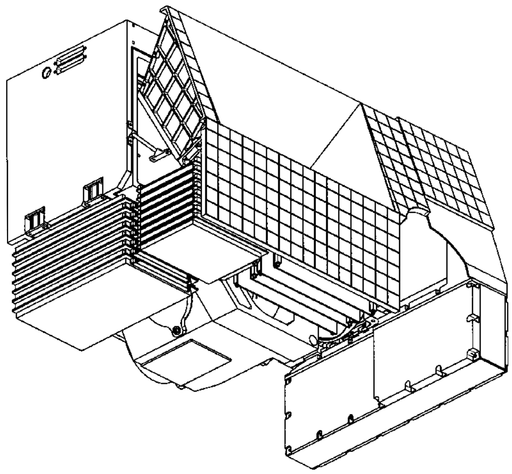
A number of other CrIS trade studies were performed in order to arrive at the final CrIS sensor configuration. While these trades were somewhat less critical than the ones described in the previous section, each trade study did have an impact on the ultimate CrIS sensor design. These other trade studies are described briefly in Table 1.

Table 1. Key CrIS Trade Study Results

CrIS Trade Study	Conclusion of Trade Study
Barrel-Roll Versus Paddle Wheel Scanner	Baseline barrel-roll scanner is higher performance (due to larger allowable aperture and improved calibration) and lower cost
Telescope Before / After Interferometer	Telescope after interferometer permits larger aperture and higher performance with virtually no cost impact
Flat Mirror Versus Cornercube Interferometer	Cornercube system is slightly lower performance due to smaller aperture; slightly higher risk due to tight cube thermal stability requirements; slightly higher cost
Beamsplitter Type	ZnSe is lower cost and risk due to handling and durability considerations; no impact on EDR performance
Telescope Type	3-Element On-Axis Reflective telescope has superior image quality performance; lower cost; improves FOV shape match; easier to upgrade to larger arrays
Telescope Cooling	Ambient-temperature telescope has negligible impact on NEdN; reduces cost through elimination of second passive cooler
Aft Optics Mounting	Mounting aft optics dichroics directly to first stage of passive cooler improves coregistration performance at no added cost
Detector Optics Trade	Aplanats selected as baseline due to maturity, but reflective concentrators may be examined as possible technology insertion on future flight units
Cloud Detection Sensor Trade	Separate cloud detection sensor within CrIS is higher cost; cloud clearing EDR algorithms achieve comparable performance at lower cost
DSP Versus ASIC	ASIC approach is much lower power and volume; also lower cost due to proven ITT ASIC development techniques
Centralized Versus Distributed Processing Electronics	Trade study found no significant cost difference between approaches; retained more modular distributed architecture
Centralized Versus Distributed Power Supplies	Cost reductions and thermal advantages in combining PCE and interferometer power supplies
Cross-Strapping Trade	Cross-strapping between modules eliminated as cost savings due to improvement in reliability achieved via power reductions

6. CRIS SENSOR DESIGN

The trade studies discussed in the previous section were used to identify the “best value” CrIS sensor design. Figure 7 shows our baseline CrIS sensor design, and lists many of its key design features. These features are discussed in more detail below.



- Large 8 cm Clear Aperture
- Three Spectral Bands
- 3x3 FOVs at 14 km Diameter
- Photovoltaic Detectors in All 3 Bands
- 4-Stage Passive Detector Cooler
- Plane-Mirror Interferometer With DA
- Internal Spectral Calibration
- Deep-Cavity Internal Calibration Target
- Onboard Signal Processing Electronics
- Highly Stable Sensor Structure
- Modular Construction

Figure 7. CrIS Sensor Design

Large 8 cm Aperture: As noted in the previous section, sensor aperture is a critical performance parameter, and we selected an 8 cm aperture as the largest practical aperture that could be packaged within the CrIS envelope. This conclusion was the result of extensive packaging trade studies that examined numerous optical configurations. The 8 cm system that was ultimately selected placed the main telescope behind the interferometer for minimum volume, used an all-reflective telescope for maximum throughput, used a two-tier folded optical layout for optimum packaging, and a compact set of aft optics for spectral separation. Pupil imaging is used for superior radiometric calibration capabilities.

PV Detectors. A critical CrIS design selection was the use of photovoltaic (PV) detectors in all three spectral bands. PV detectors have the important benefits of higher sensitivity and much better non-linearity, as compared to photoconductive (PC) detectors. However, PV detectors had not been demonstrated at the long LWIR wavelengths needed for CrIS, particularly at the large detector sizes needed for a pupil imager. To address this risk, prototypes of the CrIS PV detectors were built and tested by Boeing, and have demonstrated the performance required for CrIS. Other trades determined that an LWIR peak response wavelength of 14 um (rather than longer wavelengths) resulted in optimum EDR performance while minimizing the detector development risk.

4-Stage Passive Cooler. One of the key factors that enables the use of PV detectors is an innovative 4-stage passive cooler design which provides sufficiently cold temperatures for PV detectors to operate efficiently. Further, the 3rd and 4th stages of the cooler were optimized to produce the optimum detector temperatures needed in each band. This has resulted in a 3rd stage which operates at temperatures near 98K (for the MWIR and SWIR detectors), and a 4th stage which operates at temperatures near 81K (for the LWIR detectors). Because the SWIR and MWIR bands are background limited, temperatures colder than 100K offer only negligible performance improvements.

Plane Mirror Interferometer with Dynamic Alignment. The heart of the CrIS sensor is the interferometer, which converts the incoming scene radiance into modulated interference patterns, which are then detected by the FPAs. Several trade studies examined different possible interferometer configurations. In particular, the trade study focussed on the decision between a cornercube interferometer (such as that used on IASI), and a flat-mirror system that employs dynamic alignment (DA) to correct for tilts of the flat mirrors. Ultimately, the plane mirror system with DA was chosen, primarily because it provides superior radiometric accuracy, lower total cost, and improved stability of the instrument line shape (ILS function). In addition, the plane mirror system was found to be more compact, making it possible to increase the CrIS aperture to the desired 8 cm level.

Internal Spectral Calibration. An additional feature of the CrIS interferometer design is its use of a patented onboard method for spectral calibration. Most interferometers use lasers of some type to measure the positions of the moving mirror within the interferometer, so as to accurately trigger data sampling. If the wavelength of this laser is not precisely known, it can induce sizable errors in the spectral calibration of the resultant spectrum. To eliminate these errors, CrIS employs a patented[5] calibration system utilizing neon lamps (which are extremely stable spectrally). The outputs of the neon lamps are injected into the interferometer optical path, and the fringes produced by the neon energy are compared to the fringes produced by the laser; the ratio of the number of fringes can be directly used to determine the wavelength of the laser to extremely high accuracy (<5 ppm).

Deep-Cavity Calibration Target: Calibration accuracy is an important EDR performance driver, and so we have included features in the CrIS sensor to maximize its radiometric accuracy. One example is the use of a high-precision internal calibration target (ICT). The ICT is the primary calibration standard for CrIS, is traceable to NIST standards, and uses a deep-cavity, high-emissivity design. The ICT will be built by Bomem, and its design is based on other ICTs that have been successfully demonstrated on other space programs.

Structure: The CrIS structure employs innovative structural techniques designed to maximize stiffness while limiting dynamic interactions between CrIS and other sensors on the NPOESS spacecraft. The CrIS optical bench (to which all optical modules are attached) uses composites for extremely high stiffness. The overall CrIS frame is an innovative beryllium-aluminum cast structure, which provides excellent stiffness, effective damping, and low-cost manufacturing. The structure is designed to minimize alignment shifts between warm operation during ground test and cold operation on-orbit, and enables outstanding coregistration capabilities between spectral bands. It is also designed to minimize dynamic interactions between the CrIS sensor and other sensors on the NPOESS spacecraft.

Modular Construction: Another priority in developing the CrIS design was to achieve modularity; that is, dividing the CrIS sensor into several independent modules, each with a specific function. Modularity has many important advantages. Independent modules can be more easily built and tested in parallel, reducing assembly time and ensuring that fully pre-tested modules are available for integration, reducing the chances of encountering failures during sensor-level testing. Modularity also makes it far easier to make upgrades and improvements to the sensor in the future; a module can be replaced with a higher-performance unit without impacting surrounding modules.

Pre-Planned Product Improvements (P^3I): CrIS P^3I efforts are focussed on enhancing the performance of future CrIS flight units, as various technologies become mature enough to warrant incorporation into the CrIS design. P^3I was an important consideration in the CrIS design; that is, likely upgrades were identified early in the design process, and the CrIS sensor is designed to easily accommodate the most likely future upgrades with minimal impacts. These upgrades include larger than 3x3 detector arrays (e.g., 4x4 or 6x6 arrays), active coolers, and bicolor detectors. As noted above, sensor modularity greatly simplifies P^3I upgrades. For example, CrIS is designed so that the passive cooler can be directly replaced by an active cooler with minimal impacts on the rest of the sensor.

7. PROJECTED CRIS PERFORMANCE

The performance of the CrIS sensor is a significant leap forward compared to existing operational sounders. The key performance parameters of CrIS are summarized in Table 2, and its sensitivity (in terms of Noise Equivalent Spectral Radiance, or NEdN) is shown in Figure 8.

Sensor Parameter	Guaranteed Value
LWIR Band	650-1095 cm^{-1}
MWIR Band	1210-1750 cm^{-1}
SWIR Band	2155-2550 cm^{-1}
LWIR Spectral Resolution	< 0.625 cm^{-1}
MWIR Spectral Resolution	< 1.25 cm^{-1}
SWIR Spectral Resolution	< 2.5 cm^{-1}
Number of FOVs	3 x 3
FOV Diameter (Round)	14 km

Sensor Parameter	Guaranteed Value
FOV Motion (Jitter)	< 50 urad / axis
Mapping Accuracy	< 1.45 km
Absolute Radiometric Uncertainty	< 0.45% (LWIR) < 0.6% (MWIR) < 0.8% (SWIR)
Radiometric Stability	< 0.4% (LWIR) < 0.5% (MWIR) < 0.65% (SWIR)
Spectral Shift Errors	< 5 ppm

Table 2. Key CrIS Sensor Performance Parameters

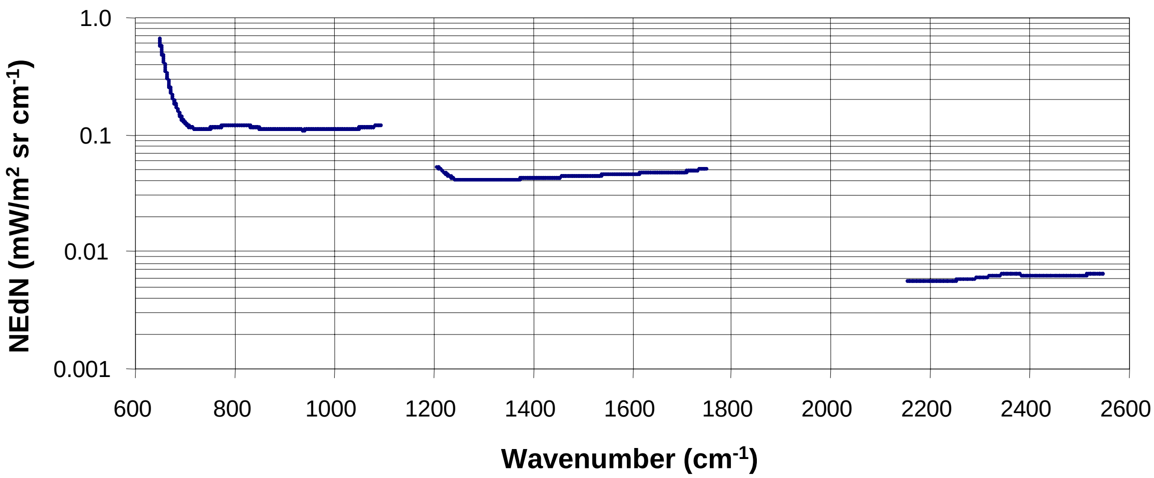


Figure 8. Noise Equivalent Spectral Radiance (NEdN) or Sensitivity of the CrIS Sensor

Considerable design efforts were concentrated on maximizing the CrIS performance parameters shown in Table 2 and Figure 8. In particular, NEdN performance is considerably better than similar types of instruments, particularly in the critical LWIR band, due to the large CrIS aperture and the use of PV detectors. Radiometric accuracy has also been a priority, and the CrIS performance is projected to be considerably less than 1% absolute uncertainty. Mapping accuracy and LOS jitter are much better than minimum requirements to support future data fusion of CrIS data with other NPOESS sensors.

CrIS EDR performance also establishes a new benchmark for meteorological sounders. Figure 9 summarizes the expected on-orbit performance of the CrIS system for each of its three primary EDRs: temperature, moisture, and pressure. These results are based on simulations that model CrIS performance under a wide range of conditions, including all types of seasonal, terrain, and cloud conditions. The results indicate typical CrIS performance averaged over the entire earth, and over a full year of operation (i.e., different seasonal conditions). Cloud fractions are based on statistical distributions for cloud type, altitude, and fraction developed from on-orbit data under the CHANCES program and from a University of Wisconsin HIRS climatology evaluation.

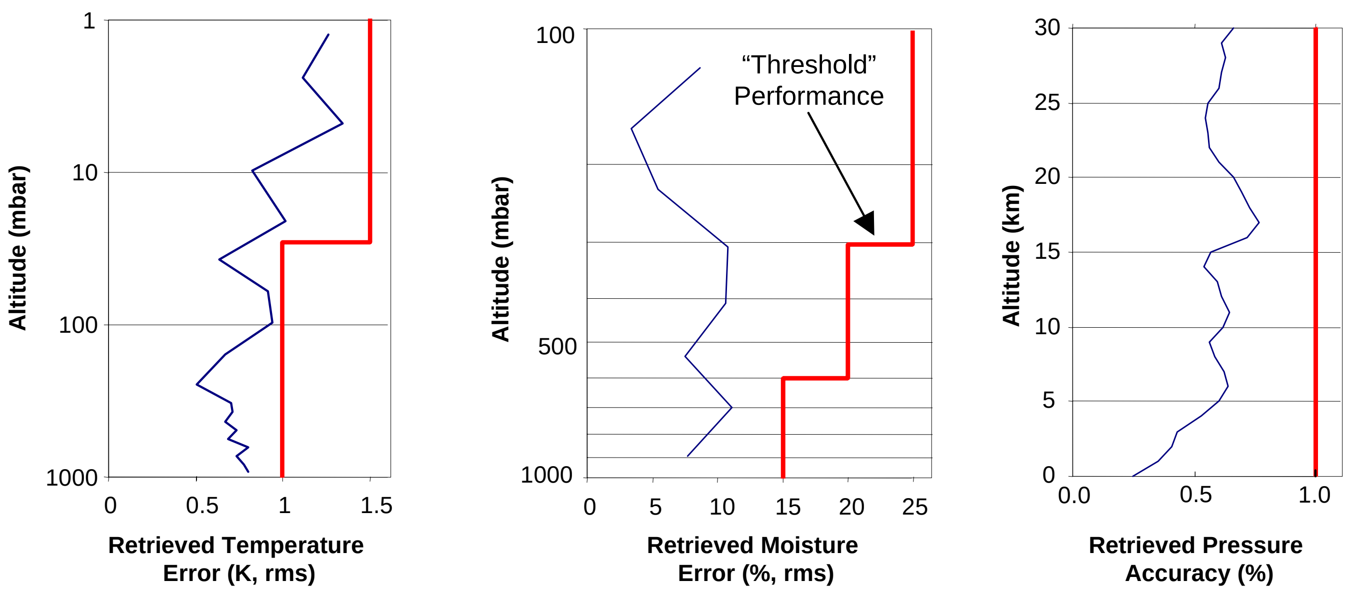


Figure 9. Expected CrIS On-Orbit EDR Performance

The graphs in Figure 9 also show lines labeled "Threshold" which indicate the minimum requirements set for CrIS by the government; in all cases, the expected CrIS performance exceeds government expectations. The results show that CrIS performance is somewhat dependent on altitude (e.g., temperature retrieval accuracy tends to fall off slowly with increasing altitude). The graphs in Figure 9 represent CrIS performance for conditions in which the 3x3 field of regard of the CrIS sensor are <50% cloudy. Performance for cases of higher cloudcover is slightly inferior, but still exceeds threshold minimum requirements.

8. CRIS DEVELOPMENT PLANS

Because CrIS is expected to be one of the sensors onboard the planned NPOESS Preparatory Project (a joint NASA / NPOESS flight demonstration program), the CrIS near-term schedule is driven by the delivery date needed to support this flight mission. The top-level CrIS development schedule is shown in Figure 10. To support the rapid development schedule without introducing risk, ITTI developed a risk mitigation program that includes development of two Engineering Development Units (EDUs). The first such unit (EDU1) was a proof-of-concept unit that demonstrated many of the key functions of the CrIS sensor design, and greatly reduced technical risk levels. Figure 11 shows a photograph of EDU1, which was built just prior to PDR. Currently, we are completing the final detailed design of the flight sensor, which will culminate in a Detailed Design Review (DDR) later this year. Following the DDR, the next version of the prototype (EDU2) will be built, and will be very similar to the flight design (although it is not currently planned to be used as a flight unit). EDU2 will then be subjected to a flight-like test program to further reduce risk. Once EDU2 test data is available, a CDR will be conducted and fabrication of the CrIS flight sensors will begin. Construction and test of the first flight unit (which will be a proto-qual unit) will be completed by in mid-2004, followed by additional flight units at 12-18 month intervals.

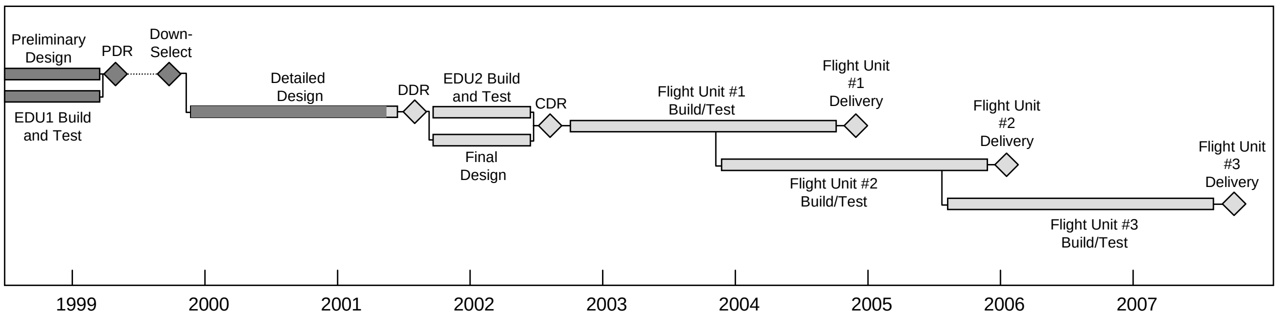


Figure 10. CrIS Top-Level Schedule Showing Key Milestones

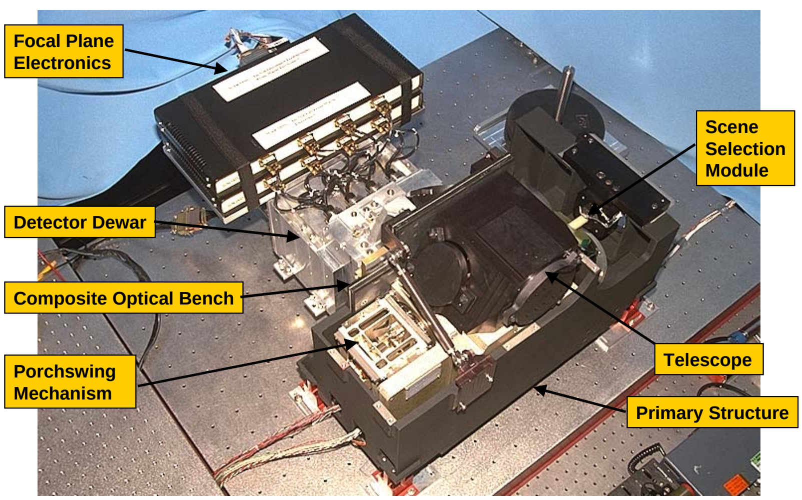


Figure 11. Photograph of the EDU1 Prototype Developed for the CrIS PDR

9. ACKNOWLEDGEMENTS

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